



GRAPHITIZED CARBON FOAM WITH PHASE CHANGE MATERIAL

THESIS

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AFIT/GA/ENY/06-M02

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THESIS

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Abstract

The transient heating and cooling responses of graphitized carbon foam infiltrated with phase change material (PCM) are studied, including thermal cycling, analytical modeling, contact resistance, and the temperature gradient through the infiltrated foam.

Infiltrating carbon foam with PCM creates an effective thermal energy storage device (TESD). The high thermal conductivity of the graphite ligaments in the foam allows rapid transfer of heat throughout the PCM volume. The PCM, chosen for its high heat capacity and high heat of fusion, stores the heat for later removal. The PCM is able to absorb a significant amount of heat without a significant increase in temperature during phase change. Three different types of carbon foam were selected for this study, and a fully-refined paraffin wax was chosen for the PCM.

Experimental samples of foam and PCM were heated on a temperature-controlled heater block from room temperature through phase change and to steady-state. Heat was then removed using a liquid-cooled cooling block. A data acquisition unit recorded temperatures throughout the experimental sample, the heater, and cooler every four seconds.

The heating and cooling responses were modeled using an exponential function. The results show a decrease in the temperature rate of change during melting and solidifying of the PCM. Multiple cycles of heating and cooling the sample produced consistent responses.

Acknowledgments

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Angelinda D. Fedden

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Nomenclature

TERMS

SUBSCRIPTS

PCM	Phase change material	in	Into the TESD
TESD	Thermal energy storage device	out	Out of the TESD
		f	Foam
T	Temperature	pcm	Phase change material
Q	Heat flux	h	Heater side
k	Thermal conductivity	g	Gap
A	Surface Area	al	Aluminum
L	Path Length	b	Bonding Material
m	Mass of foam	a	Ambient
c_p	Specific heat	w	Wall
t	Time	pc	Phase change
Q_{melt}	Heat melting PCM	i	Initial
R	Thermal resistance	c	Cooling block side
l	Material thickness	l	Into coolant
Q_{solid}	Heat released during PCM solidification		

GRAPHITIZED CARBON FOAM WITH PHASE CHANGE MATERIAL

I. Introduction

Background

Phase change materials (PCM) are useful in storing thermal energy output from various heat sources. However, a volume of phase change material alone may be slow in absorbing the heat and will melt first from the face in contact with the heat source. By infiltrating the phase change material into a carbon foam, the heat is carried throughout the entire phase change material volume. The high thermal conductivity of the ligaments of the foam allows the foam to rapidly carry heat from the heater to the phase change material for storage. This type of thermal energy storage device is a solution to prevent overheating of components caused by short-term or cyclical inputs such as certain electronic devices or the sun.

Phase change materials store heat by using thermal energy to change phase, while maintaining a constant temperature. The higher the heat of fusion, the more thermal energy the PCM can absorb. The phase change materials of interest in this project are ones that melt from solid to liquid during phase change at a temperature similar to the operating temperature of many electrical components, usually between 50-100°C.

While phase change materials offer an excellent source of thermal storage, their typically low thermal conductivities make them less effective as heat sinks. Engineers

have devised several ways to disperse heat more evenly throughout the PCM. One method is to use fins made of thermally conductive material that protrudes into the volume of PCM. Another method is to create PCM filled-chambers of thermally conductive material. The method under research in this thesis is infiltrating the PCM into a thermally-conductive porous material.

Graphitized carbon foam is an option for such a porous material. Graphite has a high thermal conductivity of up to 1800 W/mK at room temperature, which makes it useful in heat transfer. The bulk thermal conductivity for the foam is lower than the conductivity of the graphite in its ligaments, but is still very high with conductivities up to 180 W/mK. It can be made with varying degrees of density and porosity. The characteristic of porosity is determined by pore size and pores per inch. It is easily infiltrated by various phase change materials. Graphitized carbon foam is somewhat lighter than aluminum foam and significantly lighter than copper foam, making it a desirable selection among foams. Graphitized carbon foam is very easy to shape, bond to other materials, and infiltrate with various substances, further enhancing its utility in a TESD.

A factor that affects a TESD's ability to remove heat is the contact resistance between itself and the heater. Contact resistance is resistance to heat flow through the joint where two surfaces meet. Contact resistance is caused by roughness on the surfaces in contact. Particles on a rough surface will be separated from the particles on the contacting surface. Smoother surfaces will cause a lower contact resistance because more of their particles will be in contact with particles of the other surface, allowing

better conduction. Applying pressure will give the surfaces a more complete contact, reducing contact resistance. Contact resistance is difficult to estimate because every surface, even those made of the same substance, may have different surface texture characteristics. Flaws and debris may further affect contact resistance. An effective way to estimate contact resistance is to determine it experimentally.

The lumped parameter method of characterizing heat storage and removal in a TESD means that spatial variations in temperature are ignored and the temperature response is solely a function of time (1:229). This means that the temperature throughout the TESD is assumed to be equal. It also assumes that the temperature of the foam, foam/PCM interface and PCM are all equal. Since the pore sizes of the foams used in this experiment are small, this assumption should be valid. The larger the pore sizes, the greater the difference in temperature between the foam and the PCM in the center of each pore, primarily during the time when the foam has reached the PCM's melting temperature and the PCM has not yet melted completely.

Problem Statement

Previous work on this subject has shown that carbon foam infiltrated with phase change material is an effective way to remove heat from a source and provide storage until removal (9:2). This experiment adds to those findings by considering the cooling response and the cycling of the system. A comparison of the heating and cooling

responses of each period will show whether the response is consistent after being cycled repeatedly.

Hypotheses

The cooling response of a TESD should show an exponential temperature decay in cooling, with a more constant rate of temperature decay near the solidification temperature. During phase change, the temperature will not completely plateau because the temperature of the foam will continue to decrease while the PCM is solidifying. Also the paraffin does not change from fully melted to fully solid at the solidification point. It has a period of hardening over a range of temperatures.

The lumped-parameter method of characterizing the temperature response will not reflect the temperature gradient within the TESD. The longer the path through which heat must travel, the greater the gradient will be because of the thermal resistance of the material. Equation (1) shows this concept using an equation for the heat conduction through a wall (2:397). The thermal conductivity of the graphite foam is not high enough to assume isothermal heating throughout the TESD.

$$\Delta T = Q \frac{L}{kA} \quad (1)$$

ΔT = temperature difference between two points

Q = heat into system

L = path length between two points

k = thermal conductivity

A = surface area through which heat is transferred

With selection of paraffin as the PCM, the TESD should be able to undergo cycling without degradation of performance. Paraffin has a high reliability in repeated changes of phase (3:5-5). The failure in the TESD's ability to be cycled will lie in the container enclosing the foam and PCM. Whether the container can withstand the pressure of the repeated volume expansion during heating and the shrinking during solidification will determine whether the TESD can be cycled.

Methodology

Experimental samples of a TESD were fabricated from graphitized carbon foam infiltrated with the phase change material. The foam and PCM were enclosed in an acrylic tube and the bottom face was bonded with an aluminum face sheet.

Thermocouples were inserted at various locations to measure temperature throughout the sample.

The phase change material chosen for these experiments was highly refined paraffin. Paraffin is readily available at a low cost. It is so safe that it can be ingested. It has a melting temperature of 61°C, which is within the range of interest. The major drawback of paraffin is its high thermal expansion. Experiments show its volume increases about 20% when it melts, which is higher than many other types of PCM. The

specific heat capacity for solid paraffin is about 2.93 J/gK and 2.97 J/gK for liquid paraffin. The heat of fusion of paraffin is about 146 J/g (3:5-19). This is a measure of the heat input required to melt a substance, which is equal to the heat given off during solidification of the substance.

Three different types of graphitized carbon foam were used in these experiments. Foams were chosen primarily on availability. One foam was a high density foam manufactured by MER Corp. The second foam was a low density foam, also from MER. The third foam was a high density foam manufactured by Poco. Table 2 shows the density and estimated bulk thermal conductivities of the foams. The density was determined experimentally, and the thermal conductivity was given by the manufacturers.

Table 1: Foam Characteristics

Foam Type	Density g/cm³	Estimated Bulk Thermal Conductivity (W/mK)
MER high density	0.49	1-180
MER low density	0.16	0.1-50
POCO	0.53	135

Figures 1, 2, and 3 show photographs of the foams used in this study. Each photo is to the same scale. The different pore sizes of the foams are visible. The low density MER foam shown in Figure 2 has the largest pores and the POCO foam shown in Figure

1 has the smallest pores. This corresponds with the densities of the foams shown in Table 1.

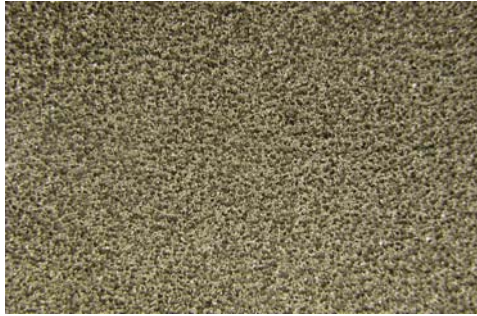


Figure 1: Photograph of Poco Foam

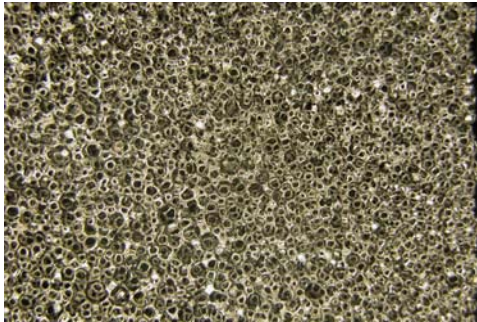


Figure 2: Photograph of Low Density MER Foam

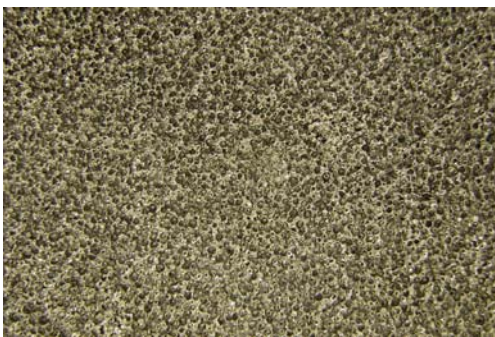


Figure 3: Photograph of High Density MER Foam

Assumptions/Limitations

Several key assumptions were made in the analysis of the foam/PCM system. First is the assumption of one-dimensional heat flow. This means that the heat from the heater block will move up the length of the TESD evenly throughout the cross-section of the block. The specific heat of the paraffin was assumed to be constant in the solid and liquid phase. It differed by only 0.04 J/gK over the phase change, so this assumption allowed accurate models.

II. Literature Review

Previous Studies

Various studies have been conducted using phase change materials infiltrated into porous materials. Studies have evaluated feasibility of such systems for heat removal and storage. Some studies have characterized various aspects of the heating and cooling of the system.

A lumped parameter method may be used to estimate the temperature in the TESD (9:4). The maximum temperature difference within a 5.6cm x 3.8cm x 2.5cm block was measured to be less than 20%. Embedding PCM into a metal matrix has been shown to improve its ability to function as a heat sink. The matrix was able to spread the heat throughout the PCM, allowing it to absorb more heat than PCM alone. The matrix material should be vacuum brazed to the surface to improve performance by reducing the resistance from the heater to the heat sink (7:9). The carbon foam allows for the volume expansion of the PCM during phase change. The shrinking of the PCM during cooling degrades thermal performance due to the reduced surface area contact between the PCM and the foam (10:8).

Phase Change Materials

When developing a container to hold a PCM, volume expansion during melting must be considered. Unless the container is perfectly sealed while under a vacuum, the voids in the foam will contain gas. Because of the volume increase of the PCM in its molten state, pressure within the container will build as it melts. A large enough void must be maintained in the container to allow for expansion of the PCM while allowing the gas in the voids to remain at a safe pressure to prevent the container from bursting (3:8-41).

Some of the factors that make a particular phase change material desirable include its thermal and physical properties. The PCM should have a high heat of fusion in order to store more heat energy. Reliable and consistent phase change is also desirable in order to ensure the system can be cycled. A PCM with low volume expansion during melting would help prevent failure due to pressure buildup in a sealed container. A PCM would preferably have a high thermal conductivity to allow less of a gradient within the volume. However, this factor can be negated by embedding thermally conductive particles within the PCM or infiltrating the PCM into a thermally conductive matrix (3:8-2).

Paraffin is a sensible choice of PCM for this experiment. Paraffin has a high heat of fusion of 146 J/g. Heats of fusion for typical PCMs can range from less than 100 to over 300 J/g. Although it has a very low thermal conductivity of approximately 0.2 W/mK, infiltrating it into the carbon foam creates a high effective conductivity throughout the combined volume. Its high wetting ability is a useful characteristic for

infiltration into the foam. Paraffin has been shown to be reliable and predictable in repeated changes of phase (3:5-5).

Graphite foam

Graphite foam can effectively increase the thermal conductivity through a volume of embedded paraffin. The foam's open structure, thermal conductivity, porosity, and other characteristics make it useful for such a purpose. The process of manufacturing the foam begins with filling a mold with pitch and then heating it under high pressure to produce a foam. After the foam is cooled and trimmed, it is heated again for several days, during which the foam becomes carbonized. Lastly, it is heated at even higher temperatures until it becomes graphitized (5:4). Foams produced from pitch have highly aligned ligaments, which increase the thermal conductivity throughout the foam (5:12).

The open porosity of the foam allows it to be infiltrated by liquids, including molten PCM. The percentage of open porosity is estimated to be up to 98% of total porosity (4:1). The foams can be produced with ranges in pore size from 30-1270 μm . The foams with larger pore sizes will typically have fewer pores per inch (ppi), and the ppi can range from 20-600. The more porous foams will have lower densities, as low as 0.016 g/cc and can be as dense as 0.62 g/cc (6:1).

III. Methodology

Thermal Energy Storage Device Overview

The thermal energy storage device (TESD) was designed to store heat for later removal. Each experimental thermal energy storage device used in this study was made from a tall rectangular section of carbon foam infiltrated with paraffin wax. The sides were encased in a square acrylic tube. The bottom face of the TESD was bonded with an aluminum sheet and the top face was left open to allow for expansion of the PCM and the gas trapped within the voids. The bottom edge of the TESD was sealed with epoxy to prevent leakage of the melted PCM.

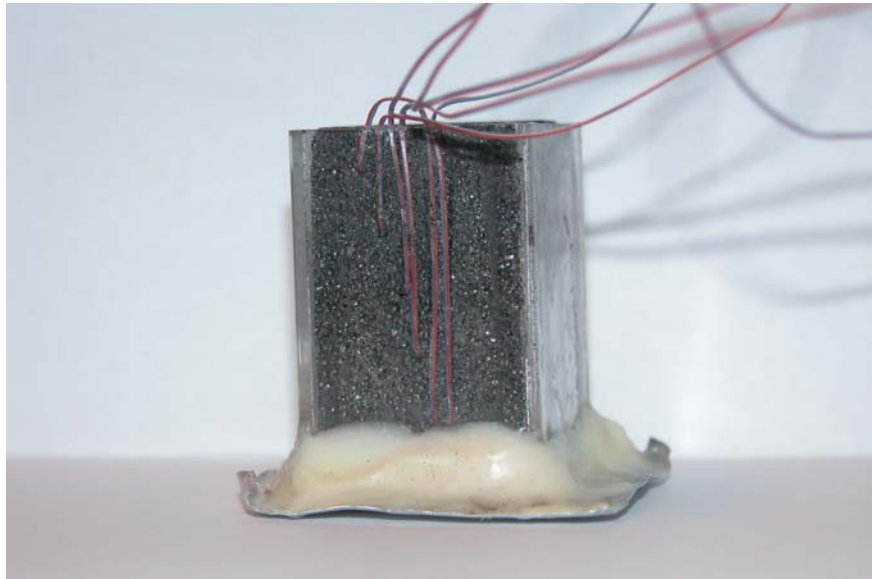


Figure 4: Photograph of TESD

Type T copper and constantan thermocouples were used to measure the temperature at different locations within the TESD. The thermocouples were inserted normal to a single face of the TESD in a diagonal pattern as shown in Figure 5. The diagonal pattern was necessary to ensure the thermocouple at one location would not interfere with the response at the location above it. The thermocouple location located nearest the heater was labeled “Site 6” and the one farthest from the heater was labeled “Site 1.”

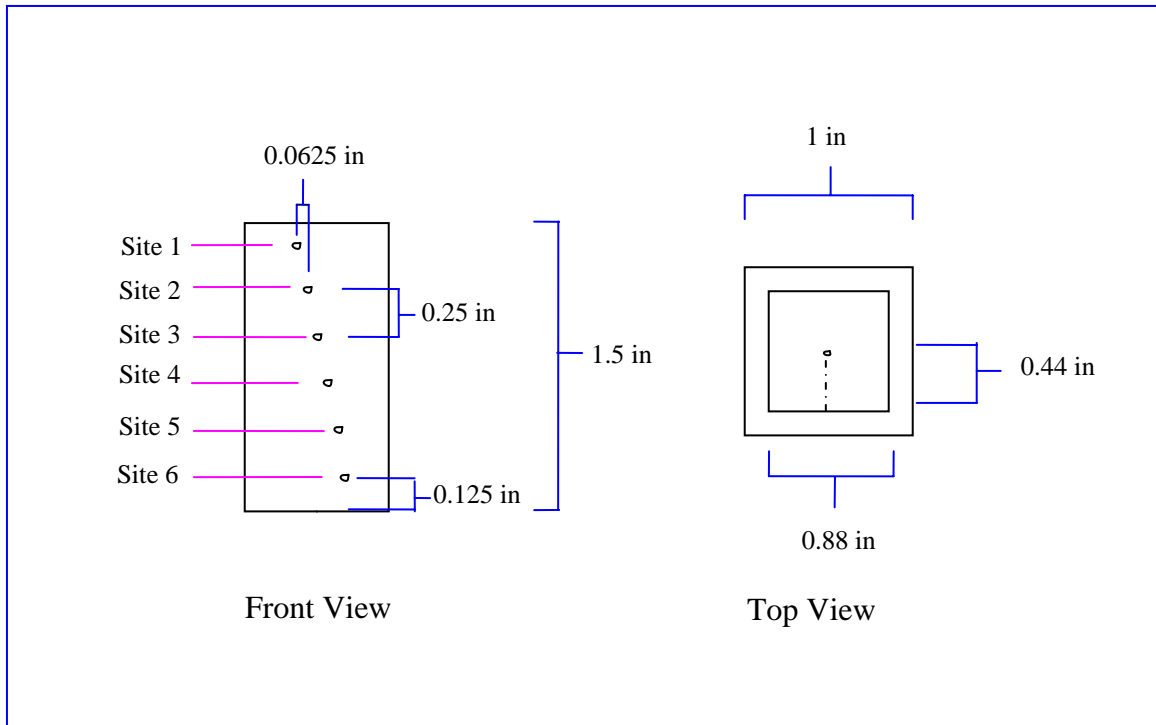


Figure 5: Thermocouple Locations

TESD Construction

A thin aluminum sheet served as the interface between the TESD and the heater. The primary function of the sheet is to keep the molten PCM from seeping out of the open pores. It must provide minimal thermal resistance, and so must be smooth, thin, and thermally conductive in plane perpendicular to the heater surface. The aluminum sheet fulfilled all these requirements. It is a foil 0.025 mm thick, similar to the wall of a soda can.

Arctic Silver® brand thermal epoxy provided a sturdy bond between the foam and the aluminum sheet. It has a thermal conductivity of over 7.5 W/mK, which is higher than many thermal epoxies on the market. Arctic Silver epoxy is easy to work with and cures at room temperature.

Each TESD was constructed in the following way. The foam was cut to size, rinsed to remove any graphite dust, and dried. After the foam was completely dry, the thin aluminum sheet was bonded to the foam. The epoxy was spread on the surface of the foam and worked into the voids with a spatula. The epoxy was also spread directly on to the aluminum sheet in order to ensure a good bond on both surfaces. After mating both surfaces, the epoxy was cured overnight at room temperature.

During the bonding process, the outermost pores of the foam were filled with epoxy. The deepest epoxy-filled void measured 0.078cm, and the thinnest layer of epoxy measured 0.013cm. The bond was strong enough to cause the foam to fail when the

aluminum was peeled away from the surface. Figure 6 shows a close up of the aluminum sheet bonded to the foam.

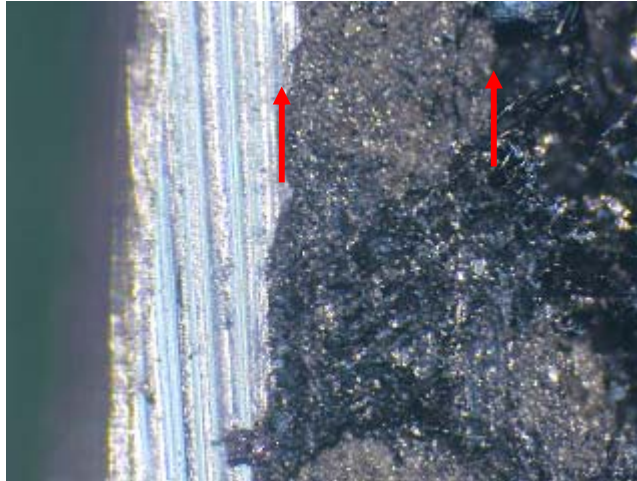


Figure 6: Bond between Foam and Aluminum

PCM infiltration into the foam was accomplished in a vacuum oven. The foam was placed in melted PCM and placed in the oven, and a vacuum was drawn to allow the PCM to flow into the foam voids previously filled with air.

The percentage of infiltration of PCM into the foam was determined by measuring the volume of the foam and the mass before infiltration, and measuring the mass after infiltration. The difference in the masses equals the mass of the PCM in the foam. The volume of PCM can easily be calculated from the density and the mass. The ratio of the PCM volume to the foam volume gives the percentage of infiltration.

Table 2: Mass and Infiltration Percentage

Foam Type	TESD Mass Before Infiltration (g)	PCM Mass (g)	% Infiltration
MER HD	9.45	11.53	66
MER LD	3.44	13.16	74
POCO	10.40	11.22	64

Test Setup

The test setup, shown in Figure 7, consists of a heater block, a cooling block, a pneumatic press, a data acquisition unit (DAU), and a computer. The heater block is made of copper with dimensions 5.6cm x 3.8cm. It has embedded thermocouples to provide temperature feedback to the computer and DAU. The cooling block has polyalphaolefin aircraft coolant running through it. It is mounted on a press controlled by pneumatics that slowly lowers it onto the TESD and applies a constant amount of pressure.

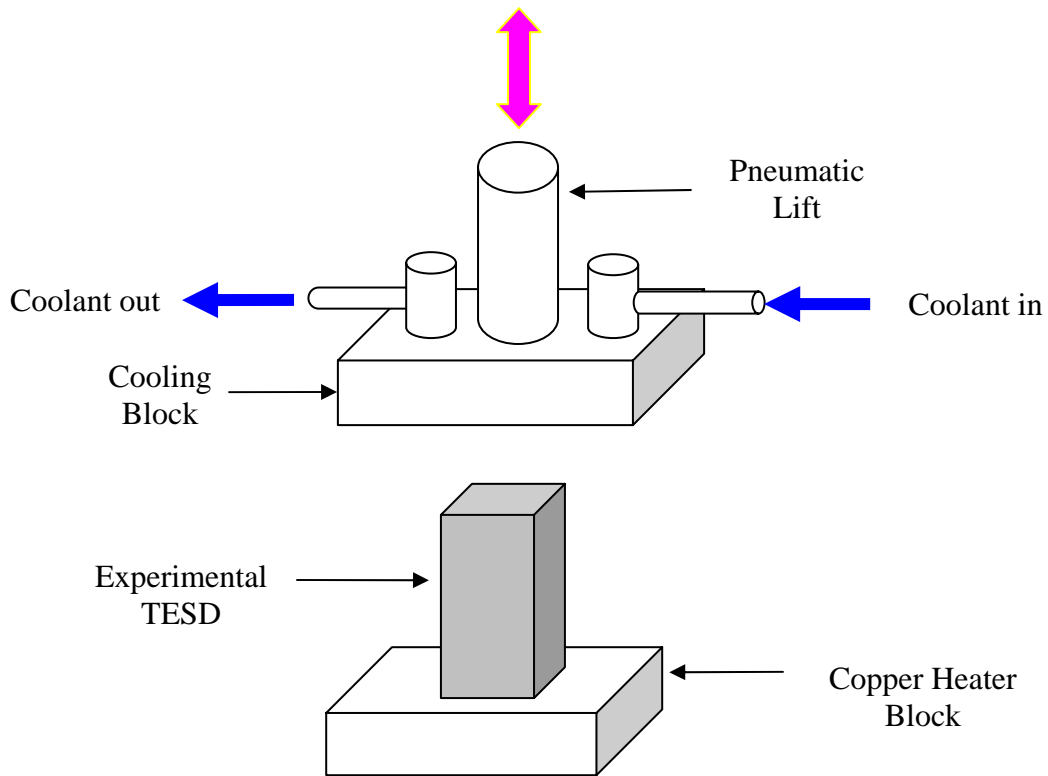


Figure 7: Test Setup Concept

The computer software controls both the heater and the cooler. It uses a non-linear feedback control system to regulate the temperature of the heater. The user inputs the desired heater temperature, cold bath temperature, and other parameters.

The data acquisition unit takes measurements of various parameters and records them approximately every four seconds. It records the temperature at the six

thermocouple locations within the block, the temperature of the heater, the temperature of the coolant, power out of the heater, and other parameters.

Test Procedure

The test procedure began with applying the phase change grease to both the surface of the heater and the TESD. Refer to Figure 7 for the test setup. The grease was intended to reduce contact resistance by filling the voids between the two surfaces.

Heater temperature was set to 75°C cold bath temperature was set to 15°C via the computer. Once the heater reached the desired temperature, the TESD was placed on the heater block. The insulating block was immediately placed on top of the TESD and then the press was dropped to hold the system in place.

Once the TESD remained on the heater for the desired amount of time, the press was lifted and the insulating block was placed between the TESD and the heater. The press was again lowered, placing the cooling block in contact with the upper TESD surface.

Limitations

The test setup was unable to keep the temperature of the heater constant. Once the TESD was placed in contact with the heater block, the temperature of the block dropped by up to 2°C and took up to 3 minutes to return to the set temperature. The

copper heater block had a large thermal mass, so it took a significant amount of time to respond to inputs from the control system. The DAU only measured the data once every four seconds, so there was a slow response time for the control system to adjust variations in temperature. These effects did not have a significant impact on the results. A comparison of the analytical model using the actual heater temperature versus the desired set temperature showed the minor differences in heater temperature caused little variation in the response.

IV. Analysis

The energy balance equation is the model for foam/PCM systems. The difference between the heat into the system minus heat out is equal to the heat stored in the system. Heat is stored in the system in two different ways. Some of the heat contributes to the softening and eventually melting of the PCM once it reaches a high enough temperature. The rest of the heat is stored in the foam and PCM of the TESD, increasing the temperature.

$$Q_{in}(t) - Q_{out}(t) = mc_p \frac{dT}{dt} + Q_{melt}(t) \quad (2)$$

Q_{in} = Power into TESD

Q_{out} = Power out of TESD

m = mass of TESD

c_p = specific heat capacity of TESD (J/gK)

T = temperature within block

t = time

Q_{melt} = Heat used to soften/melt PCM

Since the TESD is made up of foam and PCM, the product of mass times specific heat will be the sum of the product for each material.

$$mc_p = m_f c_{pf} + m_{pcm} c_{ppcm} \quad (3)$$

Q_{in} is the rate at which heat is transferred from the copper heater block into the TESD. It can be calculated by

$$Q_{in}(t) = \frac{T_h - T(t)}{R_h} \quad (4)$$

with T_h as the heater temperature, $T(t)$ as the temperature within the TESD, and R_h as the thermal resistance through the surface in contact with the heater.

The total thermal resistance, R_h , is the combination of the contact resistance due to the gap (R_g) at the joint between the heater and the TESD, plus the thermal resistance through the copper heater (R_c), aluminum (R_{al}), bonding material (R_b), and foam (R_f) to the location where the temperature is measured. Each component resistance can be calculated by

$$R = \frac{l}{kA} \quad (5)$$

l = thickness of material through plane perpendicular to heater surface

k = thermal conductivity

A = surface area of plane parallel to heater surface

and
$$R_h = R_c + R_g + R_{al} + R_b + R_f \quad (6)$$

During the heating portion of the cycle, the top of the TESD is insulated.

Therefore, Q_{out} is assumed to be the sum of heat losses through the side surfaces of the TESD, Q_l . Losses are estimated in a manner similar to calculating the heat input.

$$Q_l(t) = \frac{T(t) - T_a}{R_w} \quad (7)$$

where T_a is the temperature of the air surrounding the TESD, and R_w is the thermal resistance of the TESD wall, through the insulation.

Substituting information from Equations (3), (4) and (7) into Equation (2) gives the following equation.

$$\frac{T_h - T(t)}{R_h} - \frac{T(t) - T_a}{R_w} = (m_f c_f + m_{pcm} c_{pcm}) \frac{dT}{dt} + Q_{melt} \quad (8)$$

While the TESD is heating, much of the heat input contributes to the melting of the PCM. The paraffin begins softening several degrees before it reaches its melting point. It becomes more and more pliable until it reaches its melting temperature and then becomes liquid. As the PCM melts, the solid mass, time to complete phase change, and heat melting the PCM decrease. Numerical methods are used to estimate Q_{melt} during the heating segment after initial values are established. The subscript “n” indicates the value at the current time step, and the subscript “n-1” indicates the value at the previous time step. Each value of Q_{melt} will be plugged into the solution at each time step.

$$\begin{aligned} m_n &= m_{(n-1)} - \frac{m_{(n-1)}}{t_{pc(n-1)}} (t - t_{(n-1)}) \\ Q_{melt_n} &= \frac{m_n h_f}{t_{pc(n-1)}} \\ t_{pc_n} &= \frac{m_n h_f}{Q_{(n-1)}} \end{aligned} \quad (9)$$

m_n = mass of solid PCM

Q_{melt_n} = heat melting the PCM

t_{pc_n} = time to melt remaining solid PCM

After rearranging, the equation becomes:

$$\frac{dT}{dt} + \frac{R_h + R_w}{R_h R_w (m_f c_f + m_{pcm} c_{pcm})} T = \frac{R_w T_h + R_h T_a - R_w R_h Q_{melt}}{R_h R_w (m_f c_f + m_{pcm} c_{pcm})} \quad (10)$$

The numerical estimate of Q_{melt} from Equation (9) for each point in time can be used to obtain the solution.

$$T(t) = \left(T_i - \frac{R_h T_a + R_w T_h - R_h R_w Q_{\text{melt}}}{R_w + R_h} \right) e^{\frac{-(R_w + R_h)}{R_h R_w (m_f c_f + m_{\text{pcm}} c_{\text{pcm}})} t} + \frac{R_w T_h + R_h T_a - R_h R_w Q_{\text{melt}}}{R_w + R_h} \quad (11)$$

After the PCM is completely melted, the temperature response is modeled by a similar exponential function shifted by the amount of time for the PCM to completely change phase.

During the cooling portion of the cycle, the top surface of the TESD is exposed to the cooling block, and the lower surface is insulated. The temperature response is estimated in a manner similar to the heating response, except with heat removal instead of input. From Equation (2), Q_{in} becomes zero because there is no heat input. Q_{out} becomes Q_l , the losses, plus Q_r , the heat removed by the cooling block. Instead of having heat used to melt the PCM as in the heating segment, the phase change material releases heat while it is solidifying during the cooling segment.

$$Q_r(t) = \frac{T(t) - T_c}{R_c} \quad (12)$$

Q_r = heat removed by cooling block

T = temperature within block

T_c = temperature of the cooling block

R_c = resistance through foam to the cooler

The resistance through the foam to the cooling block can be estimated by summing the resistance from the location under investigation through the foam, R_f , plus

the contact resistance through the foam-cooler interface R_g , plus the resistance from the surface into the coolant, R_l .

$$R_c = R_f + R_g + R_l \quad (13)$$

Combining Equations (2), (3), (7) and (12) give the following differential equation:

$$-\frac{(T(t)-T_a)}{R_w} - \frac{(T(t)-T_c)}{R_c} = (m_f c_f + m_{pcm} c_{pcm}) \frac{dT}{dt} - Q_{solid} \quad (14)$$

Solving and considering initial conditions gives:

$$T(t) = (T_i - \frac{R_c T_a + R_w T_c + R_h R_w Q_{solid}}{R_w + R_c}) e^{\frac{-(R_w + R_c)}{R_c R_w (m_f c_f + m_{pcm} c_{pcm})} t} + \frac{R_w T_c + R_c T_a + R_c R_w Q_{solid}}{R_w + R_c} \quad (15)$$

The equations for heating and cooling can be modified to account for the different thermocouple locations by calculating the resistance at each location. The difference in temperature from one thermocouple location to the next is due to the increased thermal resistance due to the additional depth of material through which the heat must flow. The value for R_f is calculated by Equation (4) with different values of “l” for each location.

V. Results

Validation of Theory

Figure 8 shows the measured temperature response at Site 6 (0.25 inches into the TESD) of the high-density MER foam compared with the predicted response from Equation (8). The analytical response predicted the actual response well, except during phase change. Some of the differences between the actual and calculated temperature responses were due to the calculated thermal resistance. Slight misplacement of the thermocouples would lead to a miscalculation in the thermal resistance from the heater through the TESD to the location of the thermocouple. The values for specific heat and heat of fusion are estimates based on known values for similar types of paraffin wax. Plots for the POCO and low-density MER foam show a similar response and are located in Appendix A.

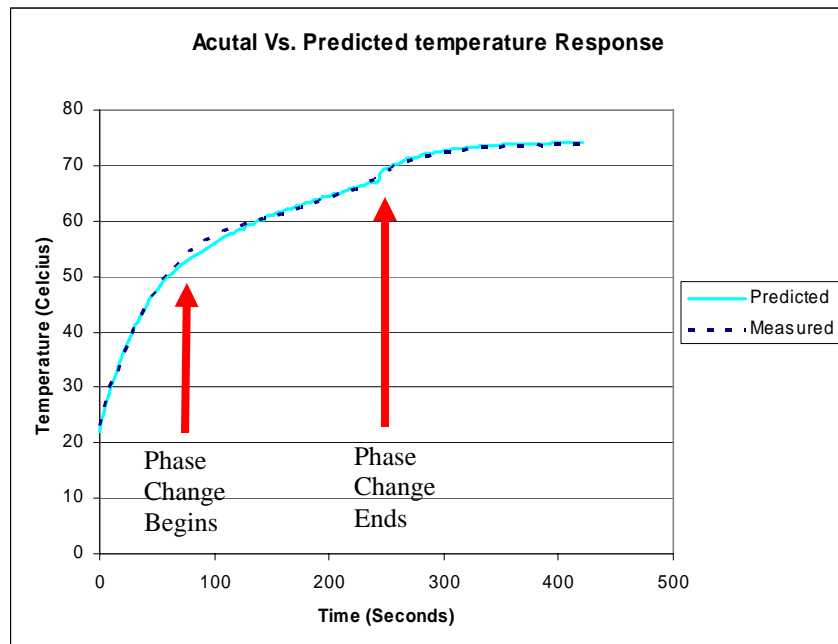


Figure 8: Actual vs. Predicted Response—High Density MER Foam

Temperature Responses

The value of infiltrating a heat sink with PCM can be seen in Figure 9. The PCM increases the time it takes for the heat sink to reach maximum temperature, giving the system a longer time to undergo heating before heat removal is necessary. For example, the unfilled TESD takes 71 seconds to reach 70°C, while the PCM-filled TESD takes 169 seconds. There is a greater difference in temperatures among the different locations within the infiltrated foam than within the unfilled foam. This is due to the PCM beginning to melt and solidify at different times at different locations within the TESD. Site 6 remains the hottest throughout heating and cooling because it is located nearest the heating block, and farthest from the cooling block. The responses for the high and low density MER foams similar and are shown in Appendix A.

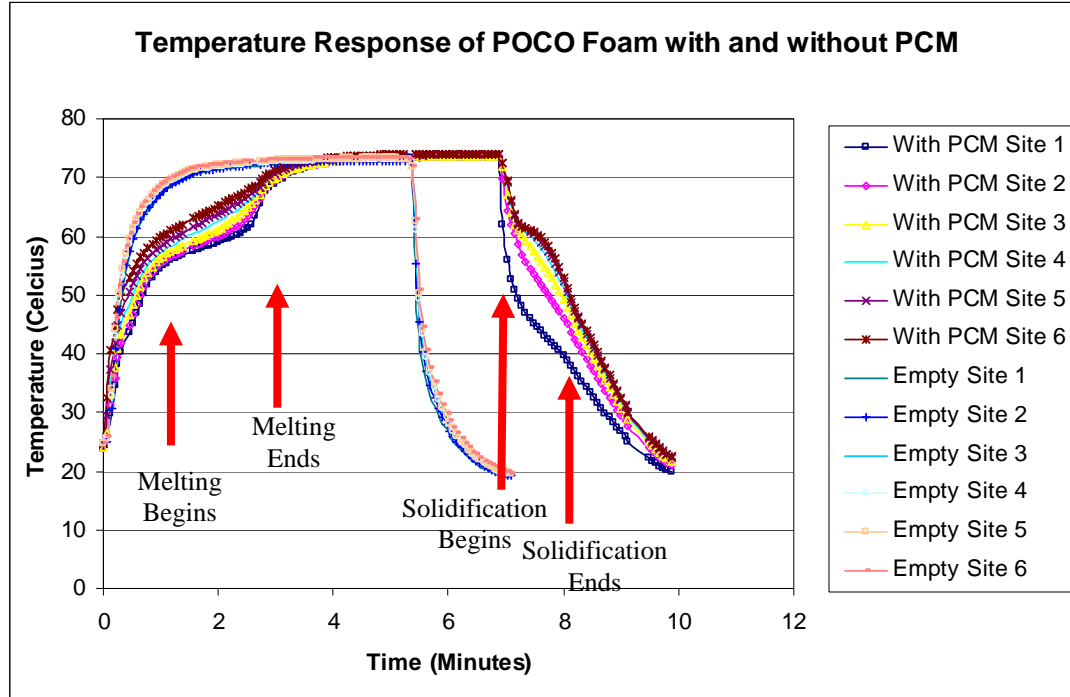


Figure 9: Response of Infiltrated vs. Uninfiltrated POCO Foam

Figure 10 shows the temperature response of the infiltrated high-density MER foam at the six locations within the block. The decreased rate of temperature rise during melting is evident on the plot, as is the decreased rate of temperature drop during solidification. A comparison of the POCO response with the MER high-density response shows that POCO heats and cools faster than the MER. The higher density of the POCO foam gives it a higher bulk thermal conductivity, thus a faster response.

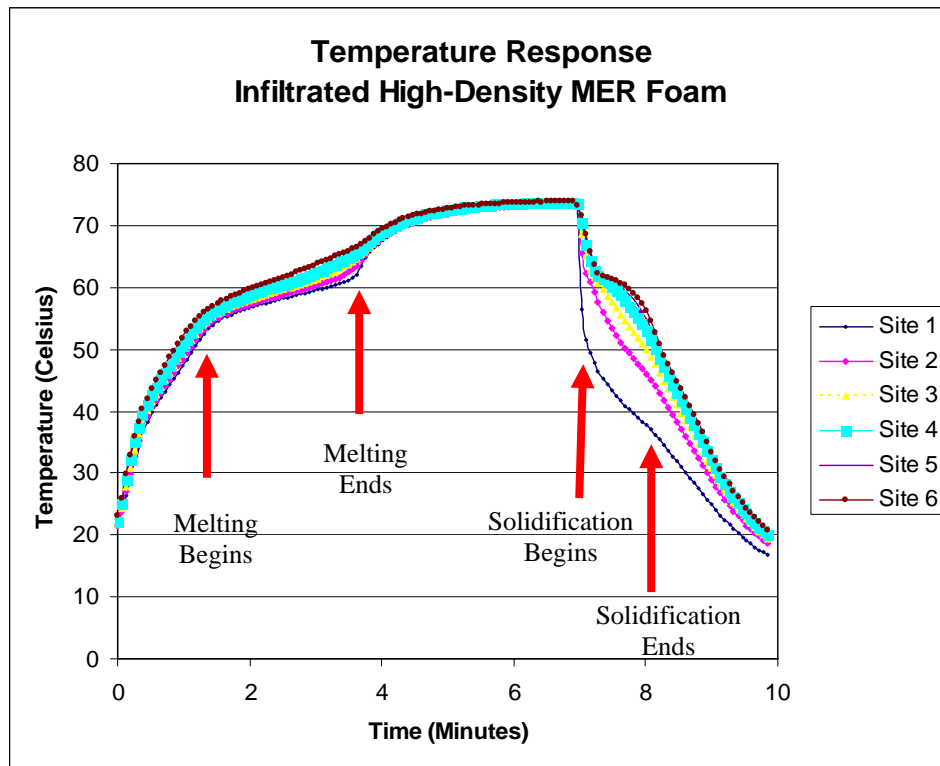


Figure 10: Temperature Response of High Density MER Foam

Figure 11 more clearly shows the maximum temperature difference from the TESD response shown in Figure 10. It shows the difference in temperature between the thermocouple location closest to the heater (site 6) and the location closest to the cooler (site 1). The temperature difference decreases during the time when the PCM is melting.

This is due to the decreased rate of temperature increase during melting. Since the PCM surrounding site 6 begins melting first, the gap in temperature decreases. Once the PCM at site 6 is completely melted, the PCM at site 1 is still melting, so the temperature gap rises again. Once PCM melting is complete throughout the TESD, the difference decreases again.

The temperature difference increases during the phase change segment while cooling because the PCM nearest the cooling block solidifies first, while the PCM at site 6 is still melted. During solidification, heat is released. Once solidification is complete, the temperature of the PCM and surrounding foam drops at a more rapid rate. Since this happens at different times within the block, the temperature of the block site nearest the cooler drops faster than the other site.

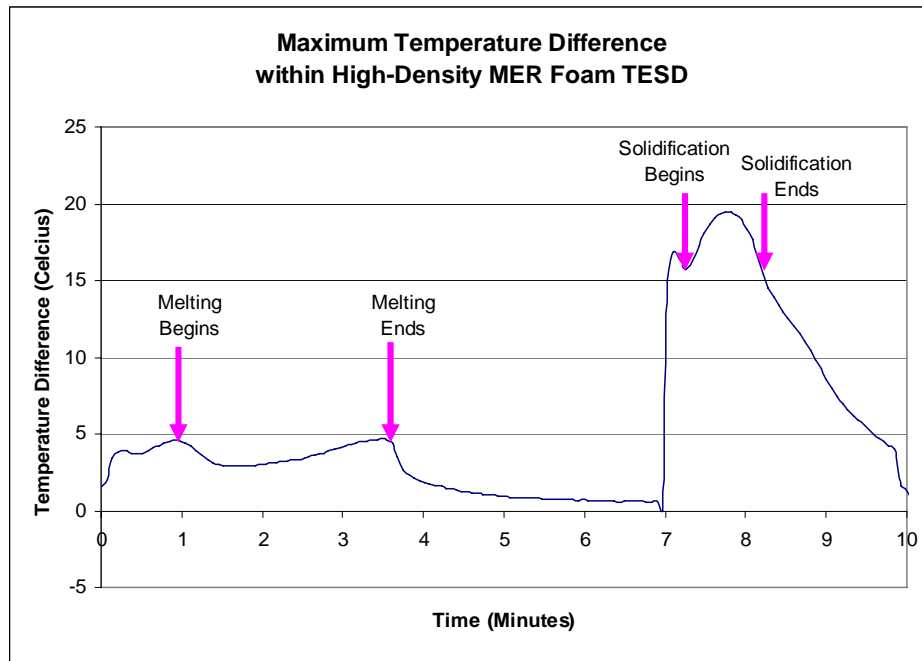


Figure 11: Max Temperature Difference—High Density MER Foam

The analysis of the temperature difference within the TESD shows that there is a significant range of temperatures from the side closest to the heater to the side closest to the cooler. However, the rates of change of temperature are very similar at the various locations within the TESD, as seen in Figure 12. The large negative spike occurs when the TESD is removed from the heater and placed in contact with the cooler.

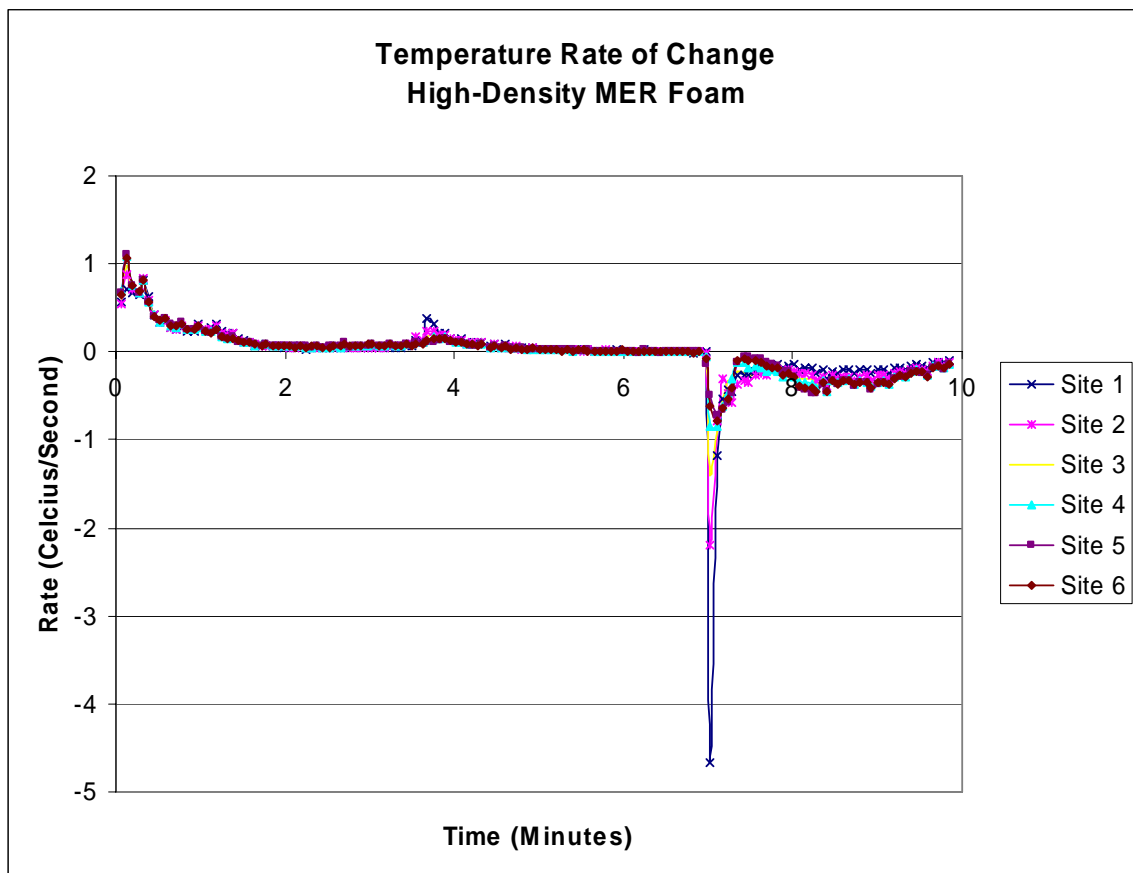


Figure 12: Temperature Rate of Change—High Density MER Foam

The low density MER foam had a wider range in temperatures between Site 1 and Site 6 than the other foams. Because the density is lower, the foam has more voids into which the PCM can infiltrate. Since the PCM has a significantly lower thermal conductivity than the foam, the infiltrated low density foam has a lower overall thermal conductivity. The higher thermal resistance causes a significant spread in temperature at the various sites as shown in Figure 13.

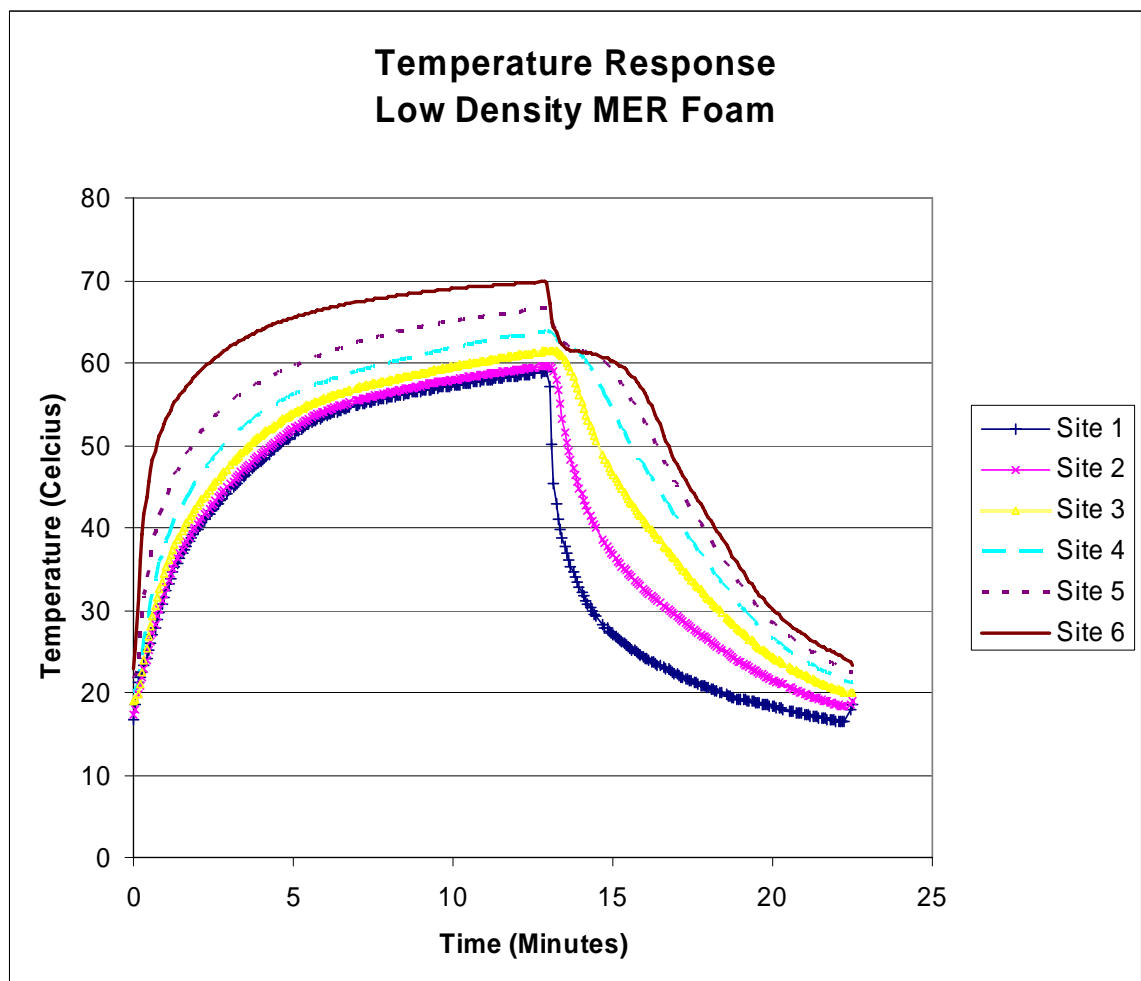


Figure 13: Temperature Response—Low Density MER Foam

Figure 14 shows a comparison of the temperature response of the high density foam vs. the low density foam. The rate of temperature increase with the lower density foam is significantly lower than the high density foam because of the higher thermal resistance, as described previously. During melting, more heat is used to melt the larger volume of PCM in the low density foam, contributing to the slower increase in temperature. Since the response for the high density foam is faster, it would be a better choice of foam if rapid cycling were necessary. However, since the low density foam contains more PCM, it is able to absorb total heat.

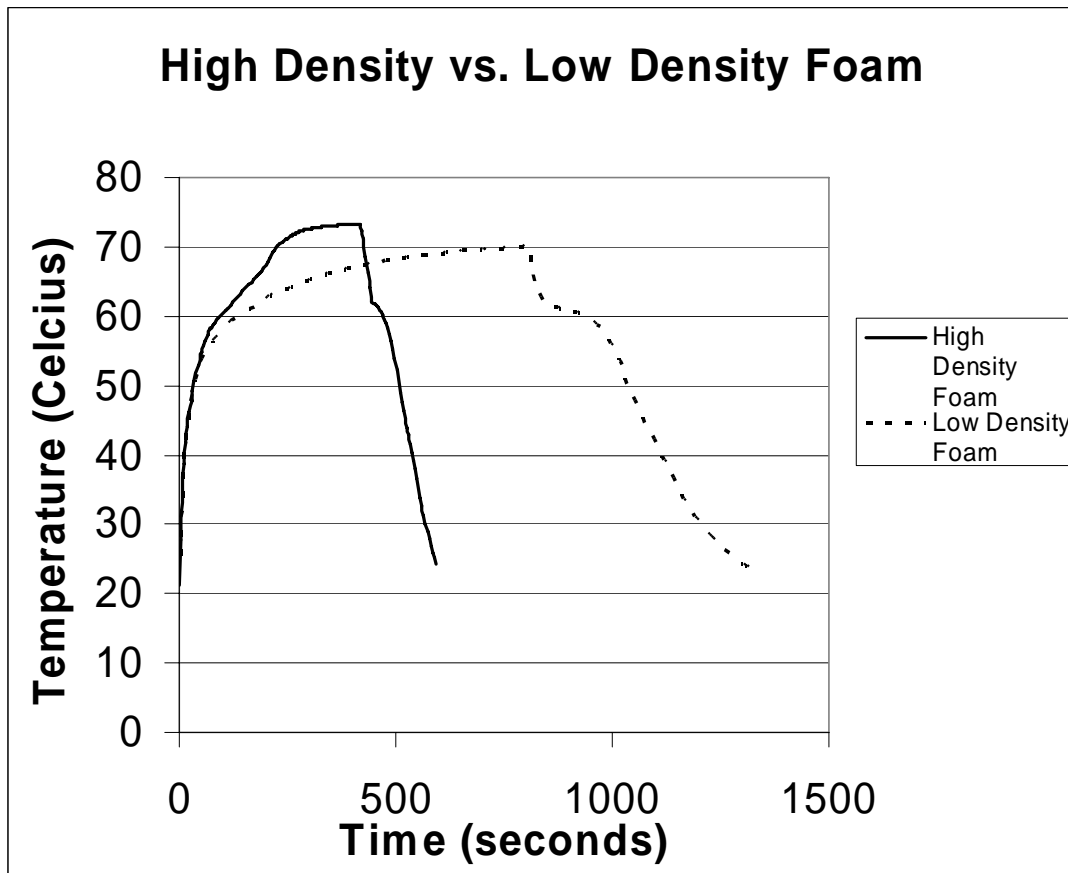


Figure 14: Temperature Response of High vs. Low Density Foam

To evaluate the effect of different contact resistances, various substances were placed between the heater block and the TESD. Figure 15 shows the response of the infiltrated high density MER foam with the various gap fillers. The contact resistance between the test article and the heater does impact the temperature response. The difference between applying the thermal grease to the heater and aluminum surfaces and having clean surfaces is minimal, though it slightly improves the rate of heat flow into the TESD. This is because the surfaces of the aluminum sheet and copper heater were smooth, thus reducing the contact resistance, so the grease had only a small effect. A thermal gap filler pad designed to reduce contact resistance by filling voids between the two surfaces in contact was tested. The gap filler pad provided worse performance than a dry contact. The ineffectiveness of the gap pad is also due to the smoothness of the two facing surfaces. If the surfaces were rough, the gap pad may have helped improve the response. A paper insulator significantly reduced the rate of heat flow. The different times it takes to reach 70°C help show the effect of the different contact resistances. The TESD took 25.53 minutes to reach 70°C with the paper insulator, 5.58 minutes with the gap filler, 3.23 minutes with the dry TESD, and 3.02 minutes for the thermal grease.

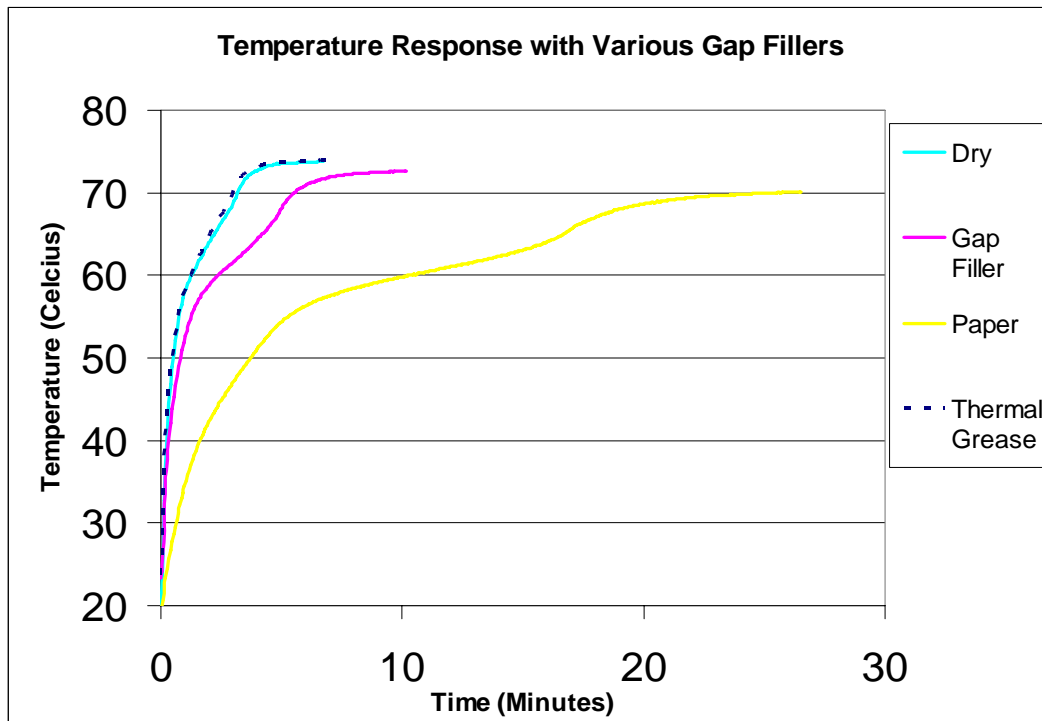


Figure 15: Temperature Response with Various Gap Fillers

The test article made with the high-density MER foam was repeatedly heated and cooled to examine its capability in cycling. Data show that the TESD can indeed be cycled repeatedly while producing consistent results. Figure 16 shows five periods of the temperature response, and Figure 17 shows an overlay of the rate response of five periods of the heating/cooling cycle. Slight variations in the temperature response may be caused by manual interaction with the experiment, and also the settling of the PCM over periods of melting and solidifying.

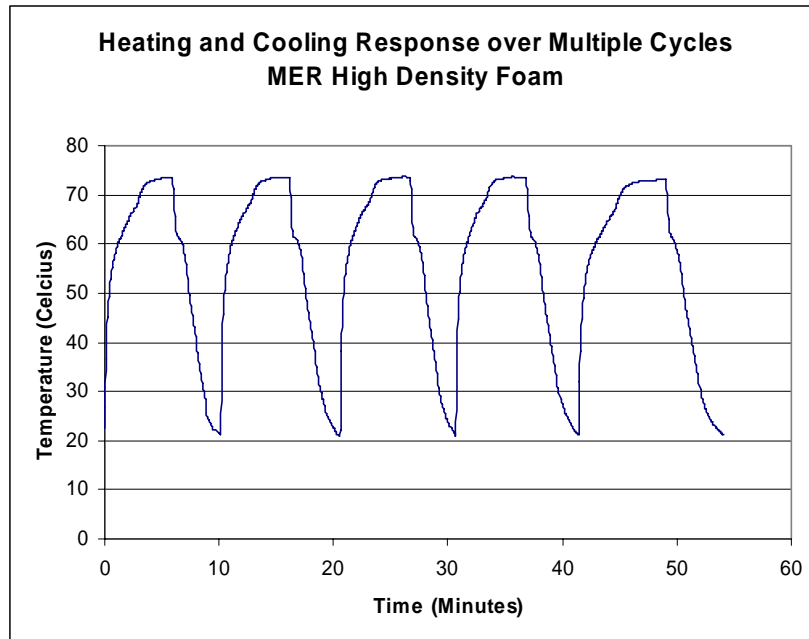


Figure 16: Cycled Response

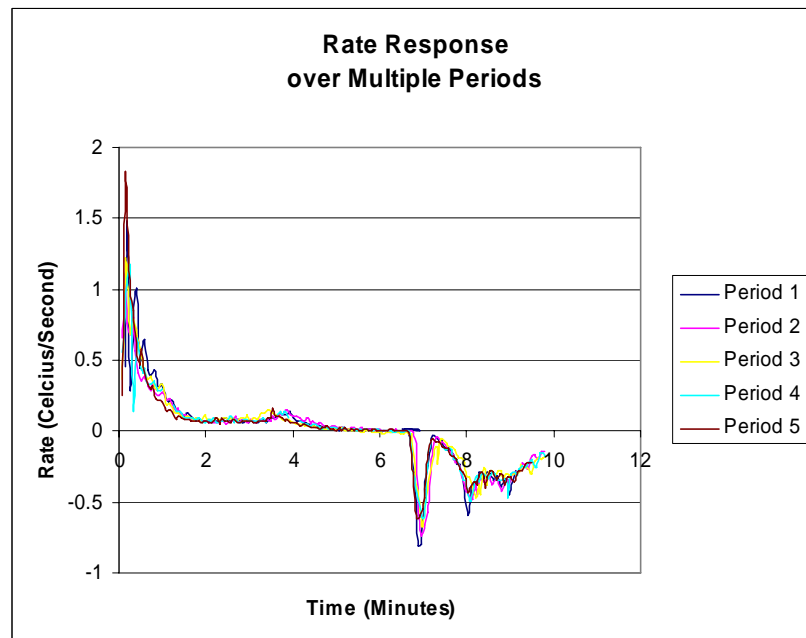


Figure 17: Rate Response over Multiple Periods

VI. Conclusions and Recommendations

Conclusions of Research

The foam infiltrated with phase change material performed as expected. The analytical representation of the system shown in Equation (11) predicted the actual temperature response of the TESDs quite accurately.

The thermal response reveals decreased rates of temperature increase in the heating portion and temperature decrease in the cooling portion during phase change. This is due to some of the input thermal energy being used to melt the paraffin.

These experiments show that the carbon foam infiltrated with phase change material can be cycled repeatedly with consistent performance. This result is necessary for this type of thermal energy storage device to be implemented on real-world systems.

The range in temperatures at different locations throughout the block depend on the bulk thermal conductivity of the foam infiltrated with phase change material. The less dense foam has a lower thermal conductivity, and therefore a greater spread in temperatures. The less dense foam was able to slow the rate of temperature increase more than the more dense foam.

Significance of Research

A thermal energy storage device made of carbon foam infiltrated with PCM can be used to remove heat from a source and store it until removal at a later time. The phase change material selected must have a melt temperature slightly below the operating temperature of the system.

Selection of the density of foam depends on the intended use. If the system needs rapid heat storage and removal, a higher density foam would be the preferred choice. If a large amount of heat storage is required, the low density foam would allow more infiltration of PCM and therefore more heat storage. A need for rapid cycling would require a higher density foam.

Recommendations for Action

A method must be developed to completely encase the TES device in order to use it in real-world applications. One possibility would be to use slightly flexible walls for the sides. Another possibility would be to encapsulate the infiltrated foam while in a vacuum. This method would remove the air from remaining voids so the expanding PCM could move into the voids as it heats.

The test setup needs to be redesigned to use a heater with a smaller thermal mass. It should be able to provide variable heat inputs as desired. This would also allow experiments using a constant power input. Experiments with a constant power input

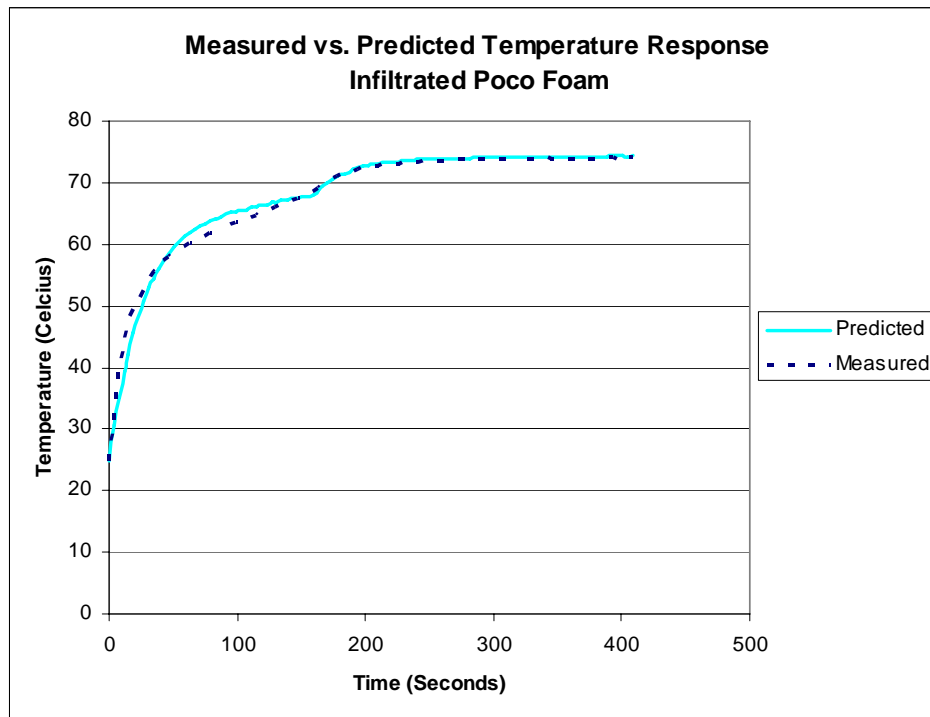
instead of constant temperature input would provide more useful information on the effectiveness of the TESD on real-world systems.

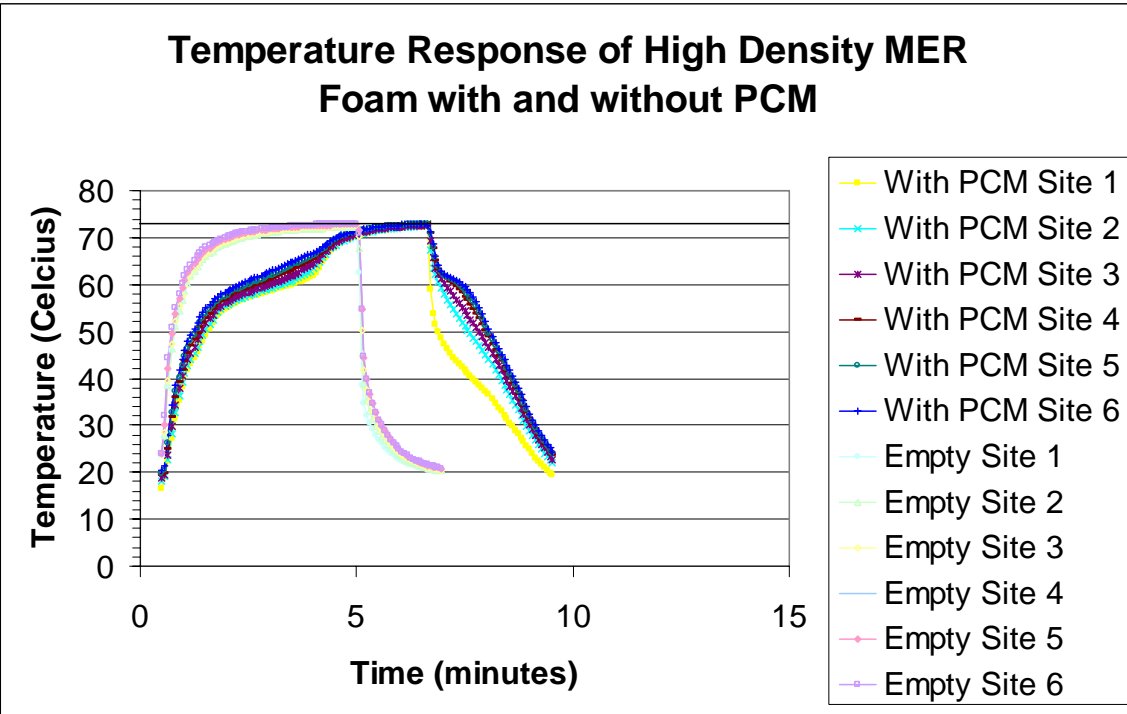
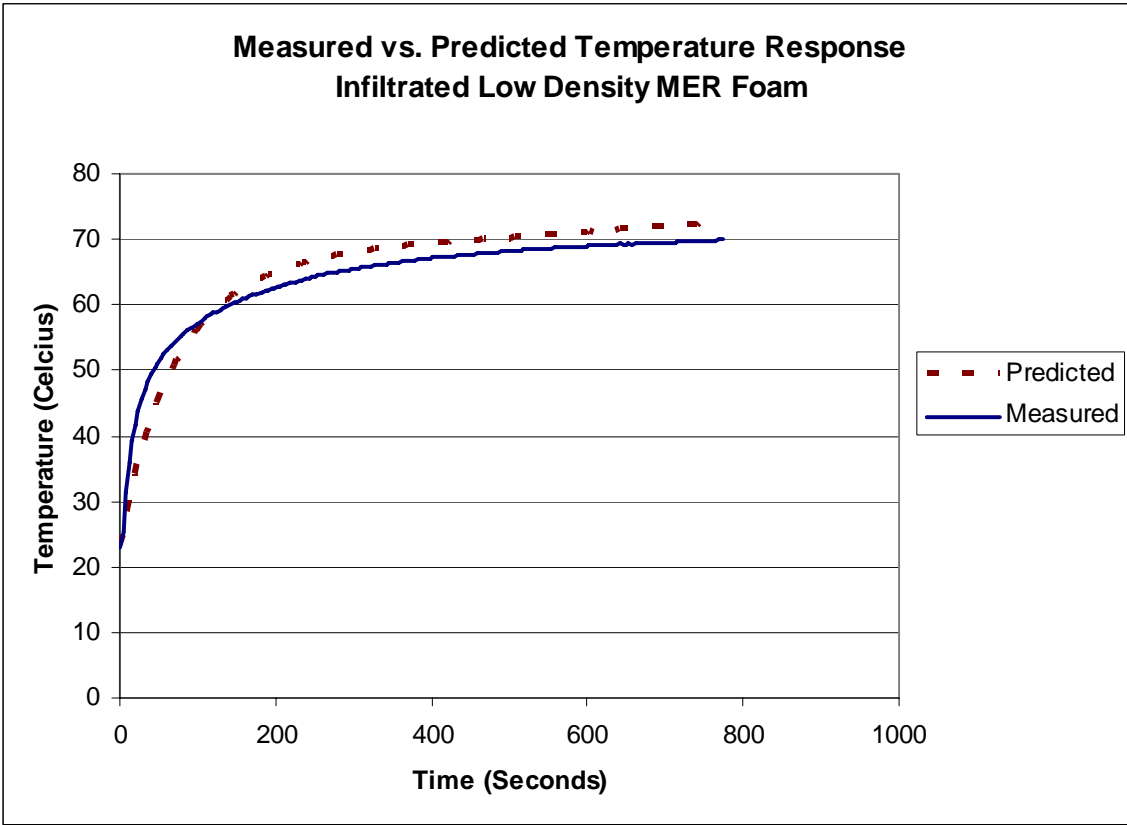
Chromotomographical (CT) mapping of the PCM infiltration should be conducted to determine the movement or settling of PCM throughout the foam. A comparison of before use and after one period of heating and cooling can show if the melted PCM settles due to gravity. A scan after multiple cycles of heating and cooling will show the extent of settling over time. A CT scan while the PCM is melted would show the extent of the expansion into the voids of the foam.

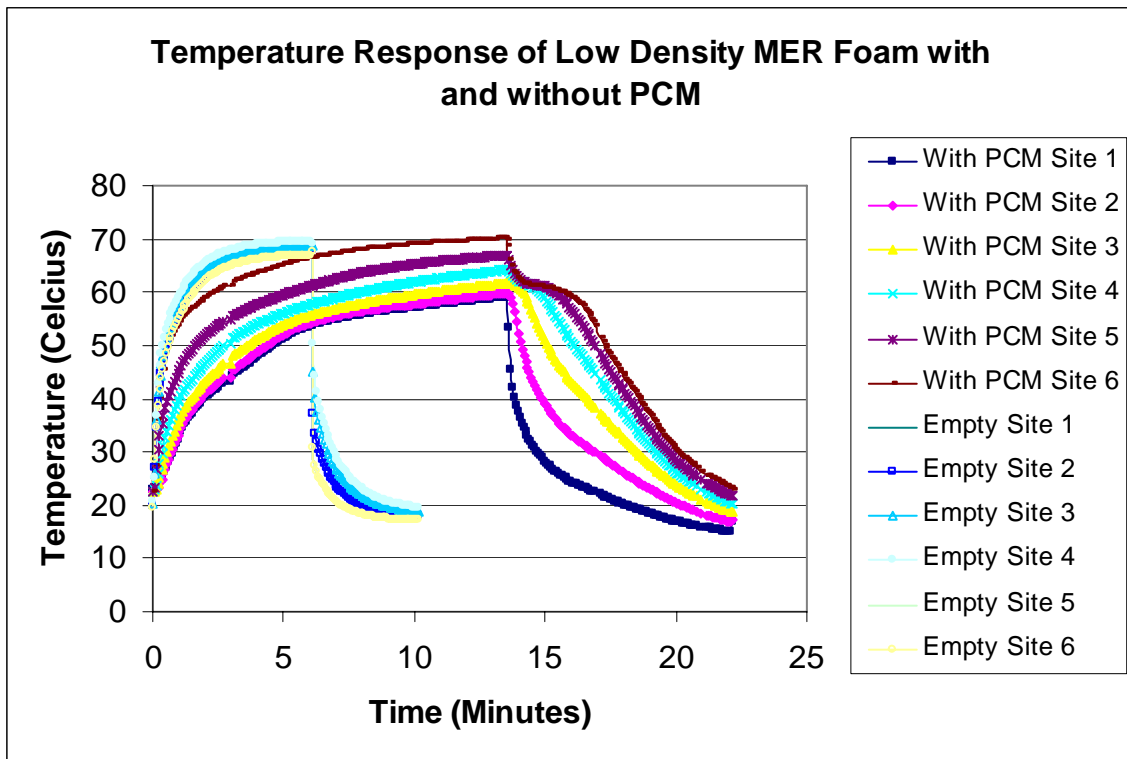
Tests should be conducted in low gravity environments. Gravity may draw the melted PCM toward the bottom of the TESD. Performance may differ if the PCM is more evenly distributed throughout the foam volume.

Appendix A: Additional Plots

Appendix A contains plots of the measured vs. predicted responses of the POCO and low density MER foams, and the comparison plots of infiltrated foam vs. uninfiltrated foam for the high density and low density MER foams.







Appendix B: Sample Calculations

MATHCAD Calculations for Percentage of PCM Infiltration into Foam by Volume

MER High Density

$$\rho_{\text{pcm}} := .9 \frac{\text{gm}}{\text{cm}^3}$$

$$m_{\text{pcm}} := (20.76 - 9.45)\text{gm}$$

$$V_{\text{foam}} := 1.5\text{in} \cdot .879\text{in} \cdot .873\text{in}$$

$$V_{\text{pcm}} := \frac{m_{\text{pcm}}}{\rho_{\text{pcm}}}$$

$$\% \text{infiltration} := \frac{V_{\text{pcm}}}{V_{\text{foam}}} \cdot 100$$

$$\% \text{infiltration} = 66.623$$

MER Low Density

$$\rho_{\text{pcm}} := .9 \frac{\text{gm}}{\text{cm}^3}$$

$$m_{\text{pcm}} := (16.35 - 3.44)\text{gm}$$

$$V_{\text{foam}} := 1.5\text{in} \cdot .879\text{in} \cdot .873\text{in}$$

$$V_{\text{pcm}} := \frac{m_{\text{pcm}}}{\rho_{\text{pcm}}}$$

$$\% \text{infiltration} := \frac{V_{\text{pcm}}}{V_{\text{foam}}} \cdot 100$$

$$\% \text{infiltration} = 76.048$$

Pocofoam

$$\rho_{\text{pcm}} := .9 \frac{\text{gm}}{\text{cm}^3}$$

$$m_{\text{pcm}} := (21.40 - 10.40)\text{gm}$$

$$V_{\text{foam}} := 1.5\text{in} \cdot .879\text{in} \cdot .873\text{in}$$

$$V_{\text{pcm}} := \frac{m_{\text{pcm}}}{\rho_{\text{pcm}}}$$

$$\% \text{infiltration} := \frac{V_{\text{pcm}}}{V_{\text{foam}}} \cdot 100$$

$$\% \text{infiltration} = 64.797$$

MATHCAD Calculations for Thermal Resistance

Resistance from Heater to Site 6 of High Density MER TESD

$$R_{\text{copper}} := .0014 \frac{\text{K}}{\text{W}}$$

$$R_{\text{foam}} := \frac{.25 \text{ in}}{80.2 \left(\frac{\text{W}}{\text{m} \cdot \text{K}} \right) \cdot (.879 \text{ in} \cdot .876 \text{ in})}$$

$$R_{\text{foam}} = 0.159 \frac{\text{K}}{\text{W}}$$

$$R_{\text{al}} := \frac{.0028 \text{ in}}{237 \left(\frac{\text{W}}{\text{m} \cdot \text{K}} \right) \cdot (.879 \text{ in} \cdot .876 \text{ in})}$$

$$R_{\text{al}} = 6.041 \times 10^{-4} \frac{\text{K}}{\text{W}}$$

$$R_{\text{bond}} := \frac{.058 \text{ in}}{12 \left(\frac{\text{W}}{\text{m} \cdot \text{K}} \right) \cdot (.879 \text{ in} \cdot .876 \text{ in})}$$

$$R_{\text{bond}} = 0.247 \frac{\text{K}}{\text{W}}$$

$$R_{\text{grease}} := .03 \text{ m} \cdot \frac{\text{K}}{\text{W}} \cdot \frac{.008 \text{ in}}{.879 \text{ in} \cdot .876 \text{ in}}$$

$$R_{\text{grease}} = 0.012 \frac{\text{K}}{\text{W}}$$

$$R_{\text{gap}} := 0.8 \frac{\text{K}}{\text{W}}$$

$$R_{\text{h}} := R_{\text{al}} + R_{\text{bond}} + R_{\text{grease}} + R_{\text{copper}} + R_{\text{foam}} + R_{\text{gap}}$$

$$R_{\text{h}} = 1.221 \frac{\text{K}}{\text{W}}$$

Appendix C: Detailed Procedures

Detailed Procedure for TESD Construction

Each test article was constructed in the following way. The foam was cut to size using a water-cooled diamond saw. The samples were rinsed to remove any graphite dust and then allowed to dry in a 200°F oven for 5 hours and at room temperature overnight.

After the foam was completely dry, the thin aluminum sheet was bonded to the foam. First, the aluminum was cut to size using scissors. It was inspected to ensure no creases or bumps. The surface of the aluminum was prepped by rubbing sandpaper on the face to be bonded. Then both the aluminum and foam bonding surfaces were cleaned with acetone. Arctic Silver epoxy was used to bond the aluminum sheet to the foam. The epoxy was spread on the surface of the foam and massaged into the voids with the spatula. When the entire area was covered in epoxy, the excess was scraped away. The epoxy was also spread directly on to the aluminum sheet in order to ensure a good bond on both surfaces. The epoxy was cured at room temperature, 23°C.

After bonding was complete, the foam was then infiltrated with phase change material. The paraffin was melted in a glass beaker over a hot plate. The foam was placed in the beaker with the wax, and the beaker was placed in a vacuum oven preheated to 85°C. A vacuum was drawn in the oven and held for 75 minutes, which is the experimentally determined time when the air bubbles exiting the foam became scarce. The beaker was then removed from the oven. A precut piece of acrylic tube was slipped over

the foam still in the beaker. The foam was removed from the beaker and allowed to cool at room temperature. When the paraffin became solid, but while it was still soft, the acrylic case was removed. Excess wax was removed from the aluminum sheet.

The holes for the thermocouples were drilled with a micro bit. A channel along the side of the foam was cut from each hole to the top of the foam for the thermocouple wire to lie in. This was necessary to allow the snug acrylic tube to slip back over the foam without destroying the wire. The thermocouples were then inserted into the holes and laid into the channels.

The acrylic case was gently slipped back over the foam, ensuring that none of the thermocouple wires were disrupted. The lower edge of the case and the exposed aluminum were thoroughly cleaned with mineral spirits. The edge was sealed with Plastic Fusion® plastic epoxy. The epoxy cured at room temperature for 24 hours. The top of the test articles were left open to allow for expansion of the PCM

Detailed Experiment Procedure

1. Set copper heater block to 75°C and cooler to 15°C via computer.
2. Apply thermal compound to surface of heater block and TESD.
3. Once heater reaches temperature, place TESD on heater.
4. Immediately place insulating block on top.
5. Lower pneumatic press into place.
6. Once TESD remains on the heater for desired time, raise the press.
7. Immediately move insulating block underneath TESD.
8. Lower the cooling block onto test article using the pneumatic press.
9. Allow the TESD to cool to desired temperature and repeat if cycling is desired.

Bibliography

1. Bejan, Adrian, and Allan D. Kraus. *Heat Transfer Handbook*. John Wiley & Sons, 2003.
2. Çengel, Yunus A. *Introduction to Thermodynamics and Heat Transfer*. Irwin/McGraw-Hill, 1997.
3. Hale, D. V., M. J. Hoover, and M. J. O'Neil. *Phase Change Materials Handbook*, NASA CR-61363, September 1971.
4. Klett, James. "High Thermal Conductivity Graphite Foam." <http://www.ms.ornl.gov/researchgroups/CMT/foam/foams.htm>. 5 March 2006.
5. Klett, James. "ORNL High Conductivity Graphitic Foams." <http://www.ms.ornl.gov/researchgroups/CMT/foam/overview.pdf>. 5 March 2006.
6. "Materials and Electrochemical Research Corporation: Carbon-Graphite Foam." <http://www.mercorp.com/mercorp/tech3a.htm>. 5 March 2006.
7. O'Connor, John P. and Richard M. Weber. "Thermal Management of Electronic Packages Using Solid-to-Liquid Phase Change Techniques," *International Journal of Microcircuits and Electronic Packaging*, vol. 20, no. 4, pp. 593-601, 1998.
8. "Poco Graphite – Thermal Management Materials." <http://www.poco.com/thermal/foam.asp>.
9. Wierschke, Kevin. *Thermal Characteristics of Pitched Based Carbon Foam and Phase Change Materials*. MS Thesis, Graduate School of Engineering, Air Force Institute of Technology (AETC), Wright-Patterson AFB, OH, March 2005. AFIT/GSS/ENY/05-M05.
10. Wirtz, Richard, et al. "Non-Metallic and Structurally Efficient Thermal Energy Storage Composites for Avionics Temperature Control, Part I: Thermal Characterization," *42nd AIAA Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, 5-8 January 2004. AIAA-2004-0343.

Vita

Captain Angelinda D. Fedden graduated from Land O' Lakes High School in Land O'Lakes, Florida. She entered undergraduate studies at the U.S. Air Force Academy where she graduated with a Bachelor of Science degree in Astronautical Engineering in May 2001. She was also commissioned through the Academy in May 2001.

Her first assignment was at Wright-Patterson AFB as a Satellite Ground Systems Engineer at the National Air & Space Intelligence Center (NASIC) beginning in August 2001. In September 2003, she became the executive officer of the Space and Missiles directorate at NASIC. In September 2004, she entered the Graduate School of Engineering and Management, Air Force Institute of Technology. Upon graduation, she will be assigned to the Space Warfare Center at Schriever AFB.

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